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The development of calibration-based reasoning about collision events in young infants

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Abstract

Previous research indicates that, when shown a collision between a moving and a stationary object, 11-month-old infants believe that the size of the moving object affects how far the stationary object is displaced. The present experiments examined whether 6.5- and 5.5-month-old infants hold the same belief. The infants sat in front of a horizontal track; to the left of the track was an inclined ramp. A wheeled toy bug rested on the track at the bottom of the ramp. The infants were habituated to an event in which a medium-size cylinder rolled down the ramp and hit the bug, propelling it to the middle of the track. Next, the infants saw two test events in which novel cylinders propelled the bug to the end of the track. The two novel cylinders were identical to the habituation cylinder in material but not in size: one was larger (large-cylinder event) and one was smaller (small-cylinder event) than the habituation cylinder. The 6.5-month-old infants, and the 5.5-month-old female infants, looked reliably longer at the small- than at the large-cylinder event. These and control results indicated that the infants (a) believed that the size of the cylinder affected the length of the bug's trajectory and (b) used the habituation event to calibrate their predictions about the test events. Unlike the other infants, the 5.5-month-old male infants tended to look equally at the small- and large-cylinder events. Further results indicated that this negative finding was not due to the infants' (a) failure to remember how far the bug rolled in the habituation event or (b) inability to use the habituation event to calibrate predictions about novel test events. Together, the present results suggest the following conclusions. First, when shown a collision between a moving and a stationary object, infants aged 5.5–6.5 months (a) believe that there is a proportional relation between the size of the moving object and the distance traveled by the stationary object and (b) can engage in calibration-based reasoning about this size/distance relation. Second, female infants precede males by a few weeks in this development, for reasons that may be related to sex differences in the maturation of depth perception. © 1998 Elsevier Science B.V. All rights reserved

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1. Introduction

Traditionally, researchers assumed that infants understand very little of the physical events that take place around them (e.g. Piaget, 1952; Piaget, 1954). With the advent of new methodologies, however, investigators began to realize that even young infants possess intuitions about the physical world (e.g. Leslie, 1984a; Baillargeon et al., 1985; Baillargeon, 1986; Hood and Willatts, 1986; Baillargeon and Graber, 1987; Leslie and Keeble, 1987). Most of these initial investigations were relatively narrow in their focus: they sought competencies where none had been expected or demonstrated before, and their perspectives tended to be static rather than developmental in nature. Experiments were designed to establish *whether* young infants possessed specific competencies, with little attention to *how* these competencies might develop over time.

Since the beginning of the 1990s, however, the exploration of infants' physical world has undergone a dramatic change. Issues of development are now at the core of many research enterprises (e.g. Spelke et al., 1992; Baillargeon, 1995; Oakes and Cohen, 1995; Xu and Carey, 1996; Needham et al., 1997; Wilcox and Baillargeon, 1998). Although these investigators vary widely in the facets of physical knowledge that they study, all agree that the careful consideration of developmental findings – of the complex patterns of successes and failures that emerge across ages and across tasks – is one of the most powerful tools available to developmental scientists for shedding light on infants' approach to learning about the physical world.

Largely as a result of this new developmental focus, several accounts have been proposed in recent years that attempt to capture and explain important regularities in the development of infants' physical knowledge (e.g. Karmiloff-Smith, 1992; Spelke, 1994; Thelen and Smith, 1994; Baillargeon, 1995; Leslie, 1995; Mandler, 1997). Our own account (e.g. Baillargeon, 1994a, 1995, 1998; Baillargeon et al., 1995; Kotovsky and Baillargeon, 1998b; holds that infants are born with a specialized learning mechanism that facilitates their acquisition of physical knowledge. The mechanism is thought to be responsible for at least two, closely-intertwined, learning processes. One is the *formation of object and event categories*. Object categories refer to the distinct types of objects that exist in the world. We believe that infants' early object categories include: animate objects (objects such as people who possess certain facial features, can express emotions, are capable of a wide range of self-motions, and so on); inanimate self-moving objects (objects such as cars that lack many of the properties of animate objects but are capable of at least limited self-motion); and inanimate inert objects (objects such as cups that move only when acted upon). Event categories correspond to distinct ways in which objects behave or interact. We suspect that infants' early event categories include: collision events (events in which an object approaches and hits another object); arrested-motion events (events in which an object approaches and hits a broad surface such as a wall or floor); occlusion events (events in which an object becomes occluded by another, closer object or surface); and support events (events in which an object becomes supported by another object or surface).

The second process that is controlled by infants' learning mechanism is the *identification, for each event category, of an initial concept and variables*. We believe that, when learning about an event category, infants first form an initial concept centered on a simple, all-or-none distinction. With further experience, infants identify variables that elaborate and refine this initial concept, resulting in increasingly accurate predictions and interpretations over time. To illustrate this developmental pattern, consider the results of experiments on infants' knowledge about support events (e.g. Baillargeon et al., 1992; Needham and Baillargeon, 1993; R. Baillargeon, H. Raschke, and A. Needham, unpublished data; see Baillargeon, 1995 and Baillargeon et al., 1995, for reviews). In these experiments, infants aged 3–6.5 months were presented with simple support problems involving a box and a platform; the box was released in one of several positions relative to the platform (e.g. off the platform, on top of the platform, against the side of the platform, and so on), and the infants judged whether the box should remain stable when released. The results indicated that, by 3 months of age, infants have formed an initial concept centered on a contact/no-contact distinction: they expect the box to fall if released off the platform and to remain stable otherwise. At this stage, any contact with the platform is deemed sufficient to ensure the box's stability. At least two variables are identified between 3 and 6.5 months of age. First, infants become aware that the *type of contact* between the box and the platform must be taken into account when judging the box's stability. Infants initially assume that the box will remain stable if released either on the top or against the side of the platform. However, by 4 to 5.5 months of age (females precede males by a few weeks in this development), infants distinguish between these two types of contact and recognize that only the first can lead to stability. Second, infants begin to appreciate that the *amount of contact* between the box and the platform affects the box's stability. Initially, infants believe that the box will be stable even if only a small portion (e.g. the left 15%) of its bottom surface rests on the platform. By 6.5 months of age, however, infants expect the box to fall unless a large portion of its bottom surface is supported.

What is the nature of the learning mechanism that directs infants' formation of event categories and identification of initial concepts and variables? One way to shed light on this question is to investigate distinct event categories and trace their respective developmental courses. We believe that examination of the sequence of variables that emerges for each event category – what variables are identified, when they are identified, and how they come to be identified – can yield important insights about the strengths and limitations of infants' learning mechanism.

In this context, we have begun a series of experiments on the development of infants' knowledge about collision events between inert objects (e.g. Kotovsky, 1992; Kotovsky and Baillargeon, 1994; Kotovsky and Baillargeon, 1998a, 1998b.

The goal of this research program is (a) to confirm that collision events, like support events, lend themselves to a developmental description involving an initial concept and variables and (b) to specify the sequence of variables that infants identify in the course of learning about collision events. Is it the case that infants initially expect any collision between a moving and a stationary object to result in a displacement? Do infants then go on to identify variables that enable them to predict more and more accurately whether a stationary object is likely to be displaced when hit, and how far or how fast it is likely to be displaced? The present research was conducted as a part of this general enterprise and focused on 5.5- and 6.5-month-old infants' reasoning about collision events. Before describing these experiments, however, we first review prior findings from our laboratory and elsewhere.

1.1. *Infants' knowledge about collision events*

At the time that we began our research, there were already several reports in the developmental literature of experiments in which infants were presented with collision events (e.g. Leslie, 1982; Leslie, 1984b; Baillargeon, 1986; Leslie and Keeble, 1987; Baillargeon and DeVos, 1991; Spelke et al., 1992; Cohen and Oakes, 1993; Oakes, 1994). However, these investigations generally focused on issues very different from those explored here, for two reasons. First, we were primarily interested in infants' reasoning about inert objects and most of the experiments involved self-moving objects: infants watched filmed or computer-generated events depicting the successive motions of two self-moving objects and judged whether the second object's motion was spontaneous or was caused by the first object's motion (e.g. Leslie, 1982; Leslie, 1984b; Leslie and Keeble, 1987; Cohen and Oakes, 1993; Oakes, 1994). In Section 7, we attempt to integrate the results of these experiments with those of the present research.

Second, the few collision experiments that made use of inert objects were not directly concerned with infants' expectations about collision events; rather, the experiments sought to determine whether infants realize that an object cannot move through the space occupied by another, occluded object (e.g. Baillargeon, 1986; Baillargeon and DeVos, 1991; Spelke et al., 1992). For example, in one series of experiments, 8-, 6.5-, and 4-month-old infants sat in front of a small screen; to the left of the screen was an inclined ramp (Baillargeon, 1986; Baillargeon and DeVos, 1991). The infants were habituated to the following event: first, the screen was raised (to reveal that there was no object behind it) and then lowered; next, a toy car rolled down the ramp, passed behind the screen, and finally exited the apparatus to the right. Following habituation, the infants saw two test events identical to the habituation event except that an object, such as a large toy mouse, now stood behind the screen; this mouse was revealed when the screen was raised. In one event (off-track event), the mouse was placed either in back or in front of the car's tracks; in the other event (on-track event), the mouse stood on top of the car's tracks, blocking its path. The 8- and 6.5-month-old infants, and the 4-month-old female infants (females succeeded at this task a few weeks before males did), looked reliably longer at the on-track than at the off-track event, suggesting that they were surprised[1] to see the car roll past the screen when the mouse stood in its path. These and control results provided evidence that the infants realized that the car could not roll through the space occupied by the hidden mouse; what the results did not reveal, however, was what the infants believed *should* have been the outcome of the collision between the car and the mouse. Did the infants expect that (a) the car would simply stop against the mouse, (b) the car would stop and the mouse would move down the track, or (c) the car and the mouse would move together down the track? Such questions led us to undertake experiments focusing directly on infants' expectations about collision events.

Our first, preliminary experiment (Kotovsky, 1992 cited in Kotovsky and Baillargeon, 1994) examined whether 5.5-month-old infants expect a stationary object to be displaced when hit by a moving object. The infants sat in front of a long horizontal track; to the left of the track was an inclined ramp. The infants were first habituated to a large cylinder that rolled down the ramp; two small stoppers prevented the cylinder from rolling past the ramp onto the track. Following habituation, a large wheeled toy bug was placed on the track, and the infants saw two test events. In both events, the cylinder rolled down the ramp as before. In one event (no-collision event), the bug was placed 10 cm from the ramp; therefore, no collision took place between the cylinder and bug, which remained stationary on the track. In the other event (collision event), the bug was positioned directly at the bottom of the ramp, between the two stoppers, so that a collision did take place between the cylinder and bug; nevertheless, the bug remained stationary, as in the no-collision event. The infants looked reliably longer at the collision than at the no-collision event. These and control results indicated that the infants expected the bug to be displaced when hit and were surprised in the collision event when this expectation was violated.

The results of this initial experiment indicated that, by 5.5 months of age, infants expect a stationary object to be displaced when hit by a moving object. Our next experiment (Kotovsky and Baillargeon, 1994) examined whether 11-month-old infants understand that how far a stationary object is displaced in a collision event depends on the moving object's size (we refer to the moving object's size rather than mass because our data are insufficient to judge which variable the infants used to form their predictions). The apparatus was identical to that in the preceding experiment. During the familiarization and test events, a cylinder rolled down the ramp and hit the bug, causing it to

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[1] When shown two events, one that is consistent with their physical expectations and one that is not, infants typically look longer at the inconsistent than at the consistent event (see Bornstein, 1985; Spelke, 1985). Infants' greater interest in the inconsistent event is often taken to indicate that they (a) detect the violation of their physical knowledge and furthermore (b) are surprised or puzzled by this violation (e.g. Spelke et al., 1992; Baillargeon, 1993, 1994b). Although no formal evidence has yet been gathered involving facial or behavioral correlates of surprise and puzzlement, we have often observed such reactions in our laboratory, and for this reason find the use of the terms 'surprise' and 'puzzlement' appropriate. Readers uncomfortable with these terms might want to view them simply as short-hand descriptions for infants' detection of violations of their knowledge.

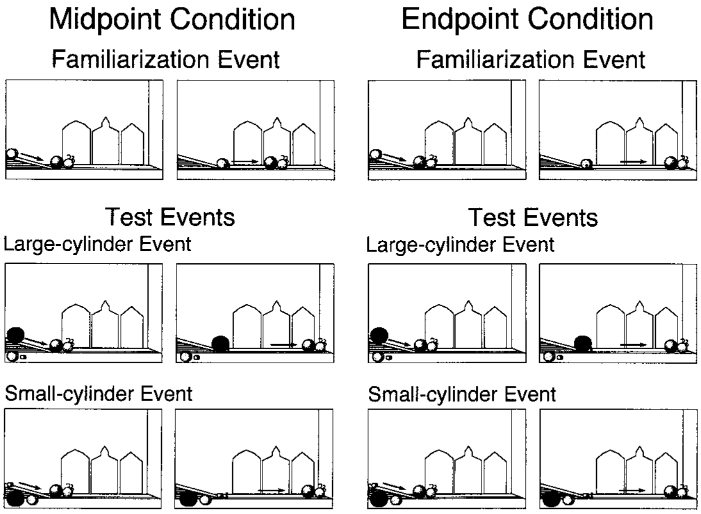

Fig. 1. Schematic drawing of the familiarization and test events shown to the 11-month-old infants in the midpoint and endpoint conditions in Kotovsky and Baillargeon (1994).

roll down the track (see Fig. 1). Three cylinders of identical material but different size and color were used in the events: there was a small orange cylinder, a medium blue cylinder, and a large yellow cylinder. The question of interest was whether the infants would expect that, all other things being equal, the larger the cylinder the farther the bug should travel down the track.

When we began designing this experiment, it immediately became clear that even adults were very poor at predicting how far the bug should roll when hit by any one cylinder: an informal survey with naive subjects yielded estimates ranging from the bug rolling a few centimeters to its crashing full speed through the far wall of the apparatus. At the same time, it was apparent that adults could form strong and consistent predictions about the length of the bug's displacement when given a *calibration point* for their predictions. Thus, after being shown that the bug rolled to the middle of the track when hit by the medium cylinder, adult subjects expected the bug to roll farther with the large but not the small cylinder. Similarly, after being shown that the bug rolled to the end of the track with the medium cylinder, adult subjects (a) expected the bug to do the same with the large cylinder and (b) found it acceptable that the bug should do the same with the small cylinder (they assumed that the track was too short to reveal effects of cylinder size). Adults thus readily used the information they were given about the medium cylinder to calibrate their predictions about the large and small cylinders.

Like our adult subjects, our 11-month-old subjects were given one of two calibration points. The infants in the *midpoint* condition watched a familiarization event in which the medium cylinder rolled down the ramp and hit the bug, propelling it to the middle of the track. The infants in the *endpoint* condition saw the same event except that the bug rolled to the end of the track. Next, the infants saw one of two test events: the medium cylinder was replaced by the large (large-cylinder event) or the small (small-cylinder event) cylinder, and both cylinders caused the bug to roll to the end of the track.

The results mirrored those obtained with the adult subjects. The infants in the midpoint condition looked reliably longer at the small- than at the large-cylinder event, whereas the infants in the endpoint condition tended to look equally at the two events. These results indicated that the infants (a) believed that the cylinder's size should affect the length of the bug's displacement and (b) used the familiarization event to calibrate their predictions about the test events. After watching the bug roll to the *middle* of the track when hit by the medium cylinder, the infants were surprised to see the bug roll to the end of the track with the small but not the large cylinder. In contrast, after watching the bug roll to the *end* of the track when hit by the medium cylinder, the infants were not surprised to see the bug do the same with either the small or the large cylinder.

These results suggested three conclusions. First, 11-month-old infants recognize that, in a collision between a moving and a stationary object, the larger the moving object, the greater the distance traveled by the stationary object. After watching the medium cylinder propel the bug to the middle of the track, the infants expected the bug to travel farther with the large but not the small cylinder. Second, by 11 months of age, infants can engage in calibration-based reasoning about the size/distance relation examined here. Depending on the specific calibration point they were given during the familiarization trials, the infants had different expectations as to how far the bug should travel when hit by the small cylinder. Thus, the infants were surprised to see the small cylinder propel the bug to the end of the track after seeing the medium cylinder propel the bug to the middle (midpoint condition) but not the end (endpoint condition) of the track. Finally, when engaging in calibration-based reasoning about the size/distance relation under examination, 11-month-old infants take into account factors such as whether an object slows to a gentle stop or whether it comes to an abrupt stop against an obstacle. The infants in the endpoint condition apparently had no expectation that the bug should travel less far with the small than with the medium cylinder, presumably because they (a) noticed during the familiarization trials that the bug stopped only when it hit the right wall of the apparatus and (b) realized, under these conditions, that the small cylinder *could* propel the bug the same distance as the medium cylinder.

The present research attempted to extend these findings to younger infants: 6.5-month-olds were tested in Experiment 1 and 5.5-month-olds in Experiment 2.

2. Experiment 1

Experiment 1 addressed two questions. First, did 6.5-month-old infants believe that, in a collision between a moving and a stationary object, the size of the moving object affects the length of the stationary object's displacement? Second, could infants this age engage in calibration-based reasoning about this size/distance relation?

The infants were tested with a procedure similar to that of our initial experiment (Kotovsky and Baillargeon, 1994), with a few exceptions. The 11-month-olds in that experiment were given three familiarization trials followed by one test trial. In a pilot experiment, 16 6.5-month-olds (range, 6 months, 9 days–7 months, 5 days; (*M*) mean, 6 months, 20 days) were shown the midpoint familiarization and test events using the same procedure. Unlike the 11-month-olds, the 6.5-month-olds (a) failed to show a reliable decline in looking time across the three familiarization trials, $F(2, 30) = 0.60$, and (b) tended to look the maximum number of seconds allowed (60 s) on the test trial regardless of whether they were presented with the small- or large-cylinder event (only two of the 16 infants looked less than 60 s on the test trial). These data suggested that younger infants might require more familiarization trials to succeed at our task.[2] Accordingly, the infants in Experiment 1 were shown the midpoint or endpoint medium-cylinder event on six or more trials, using an infant-controlled habituation procedure (see below). Following these trials, the infants saw the small- and large-cylinder events on alternate trials for six test trials.

2.1. Method

2.1.1. Subjects

The subjects were 32 healthy, full-term infants, ranging in age from 6 months, 9 days to 6 months, 29 days. Half of the infants (seven males and nine females) were assigned to the midpoint condition (M = 6 months, 19 days), and half (eight males and eight females) to the endpoint condition (M = 6 months, 19 days). An additional seven infants were tested but eliminated, five because of apparatus failure, one because he looked the maximum number of seconds (60 s) allowed on five of the six test trials, and one because he failed to attend to the events (this infant repeatedly grabbed at the stage and eventually tore loose the muslin fabric covering the lower portion of the apparatus!)

2.1.2. Apparatus

The apparatus consisted of an unpainted wooden box 122.5 cm high, 152 cm wide, and 52 cm deep that was mounted 80.5 cm above the room floor. The infants faced an opening 52.5 cm high and 150 cm wide in the front of the apparatus. The back wall of the apparatus was covered with pink poster board and was decorated with brightly-colored pictures of a barn, a church, and a house. The three buildings were arranged in a row 8.5 cm above the apparatus floor. The barn was positioned 50 cm from the left wall and the house 1 cm from the right wall. Immediately below the buildings was an opening 8.5 cm high and 91 cm long that was partially concealed by a dark blue fringe. During the experiment, the opening was used by a left hand to reach into the apparatus and reposition the bug; the hand wore a cream-colored glove 65.5 cm long.

[2] Further support for this suggestion came from midpoint and endpoint familiarization data collected with 6.5- and 5.5-month-old infants while refurbishing and adjusting our apparatus for the present research. Inspection of these familiarization data suggested that most of the infants who completed two blocks of three familiarization trials looked less on the second than on the first block of trials.

A wooden ramp 56 cm long and 13.6 cm wide stood against the left wall of the apparatus, below an opening 21 cm high and 15 cm wide that was filled with white fringe. The ramp was covered with black contact paper and was positioned 28 cm from and parallel to the front of the apparatus. At the top of the ramp was a plateau 7.6 cm high and 16 cm long; the ramp itself sloped downward at an 11° angle. The sides of the ramp were covered with panels of wood 0.5 cm thick that were cut to protrude 0.75 cm above the ramp. These side panels prevented the cylinders from rolling off the ramp. The ramp and its side panels were mounted on a strip of particle board 0.7 cm thick, 15.5 cm wide, and 56 cm long. At the bottom of the ramp and positioned 10.5 cm apart were two upright metal posts that prevented the cylinders from rolling onto the track. Each post was 10.5 cm high and 1.25 cm in diameter and was covered with black felt.

Three cylinders of different diameters and colors were used in the experiments. All three cylinders were 13.4 cm long and were made of the same plastic piping material. The largest cylinder was 11.4 cm in diameter and was painted bright yellow. The medium cylinder was 5.9 cm in diameter and was painted light blue. Finally, the smallest cylinder was 2.7 cm in diameter and was painted bright orange. The cylinders were released down the ramp by a right hand wearing a black glove 61.5 cm long; the hand entered the apparatus through the opening in the left wall at the top of the ramp.

Centered at the bottom of the ramp was a model train track 5 cm wide. The track was 96 cm long and covered the full-length of the apparatus from the bottom of the ramp to the right wall. The track rested on a strip of particle board 0.7 cm thick and 15.5 cm wide that was covered with black felt.

A brightly-colored toy bug 15 cm high, 22 cm long, and 13 cm wide was mounted on model train wheels. The bug consisted of two Styrofoam balls decorated with long blue fur; the front, smaller ball sported eyes and antennae, and the rear, larger ball was partly covered with a white flounced skirt. When the bug was placed at the bottom of the ramp, its rear portion extended between the two posts. Although it appeared that the cylinders squarely hit the bug when they rolled to the bottom of the ramp, they in fact did little more than contact the bug’s fur and skirt, with an impact insufficient to propel the bug. Fortunately, this limited impact was virtually impossible to detect: even adult subjects failed to notice it, despite repeated viewings, and assumed that the cylinders caused the bug to roll down the track (Kotovsky and Baillargeon, 1994).

When in position at the bottom of the ramp, the rear portion of the bug rested against a metal lever 0.6 cm wide and 0.6 cm deep that protruded 3 cm above the apparatus floor, between the two posts. The lever was controlled by two microswitches set in the floor of the ramp. The switches were positioned 4 and 7 cm from the bottom of the ramp; the small and medium cylinders triggered the first switch, and the large cylinder the second switch. When triggered, the switches activated a solenoid located beneath the apparatus floor; the solenoid in turn activated the lever, causing it to hit the bug. Controls attached to the solenoid made it possible for an experimenter to independently vary which switch would trigger the solenoid and how much power it would receive. With this system, any cylinder could be made to propel the bug any distance.

The infants were tested in a brightly-lit room. Four 40-W clip-on lights were attached to the front wall of the apparatus to provide additional light. Two muslin-covered frames, each 183 cm high and 71 cm wide, stood at an angle on either side of the apparatus. These frames served to isolate the infant from the experimental room. At the end of each trial, a muslin-covered frame 63 cm high and 150 cm wide was lowered in front of the opening in the front of the apparatus.

2.1.3. Events

Two experimenters worked in concert to produce the events. The first wore the black glove and manipulated the cylinders; the second wore the cream-colored glove and manipulated the bug. Numbers in parentheses indicate the time taken to perform the actions described.

2.1.3.1. Midpoint condition

2.1.3.1.1. Habituation event. At the beginning of the trial, the medium cylinder rested on the apparatus floor, 5.5 cm (at its closest point) in front of the ramp and 33 cm (again, at its closest point) from the left wall (markings on the apparatus floor ensured that the cylinder was positioned consistently across trials); the cylinder lay at an angle so that one of its ends faced the infant. To start, the black hand tapped on the cylinder at a rate of approximately 3 taps/s. When the computer signaled that the infant had looked at the cylinder for 4 cumulative seconds, the black hand grasped the cylinder and lifted it to the plateau at the top of the ramp (2 s). The black hand then moved the cylinder to the inclined portion of the ramp and released it (1 s). The cylinder rolled down the ramp (1 s) and hit the posts at the bottom of the ramp. The bug was then propelled down the track and slowed to a stop at about the middle of the track, approximately 45 cm from the bottom of the ramp (1 s). After a 4-s pause, the black hand, which had been resting at the top of the ramp, reached down (1 s) and lifted the cylinder back to the top of the ramp (1 s). Next, the cream-colored glove entered the apparatus through the opening in the back wall, grasped the front end of the bug (1 s), gently pushed it back to the bottom of the ramp (2 s), and exited the apparatus (1 s). The black hand then released the cylinder, beginning a new event cycle. Each cycle (except for the initial cycle, in which the cylinder was first tapped and then lifted to the top of the ramp) thus lasted about 13 s. Cycles were repeated without pause until the computer signaled that the trial had ended (see below). When this occurred, an experimenter lowered the curtain in front of the apparatus.

2.1.3.1.2. Small-cylinder test event. The small-cylinder test event was similar to the habituation event with a few exceptions. First, at the start of the trial, the small and large cylinders lay on either side of and about 2 cm from the medium cylinder; the cylinders were placed in descending size order with one end facing the infant, to facilitate size comparisons. Second, the small cylinder was used in the event instead of the medium cylinder. Third, the bug was propelled to the end rather than to the middle of the track. The bug took approximately 2 s to travel the length of the track and stopped only when its front end hit the apparatus's right wall. Because the bug now rolled along the track for 1 s longer and to a farther point than in the habituation event, two changes were made to ensure that the total length of each event cycle remained 13 s, as in the habituation event. One change was that the bug rested at its stopping point for 3 instead of 4 s; the other change was that the cream-colored hand pushed the bug faster so as to still return it to the bottom of the ramp in 2 s.

2.1.3.1.3. Large-cylinder test event. The large cylinder test event was identical to the small-cylinder test event except that the large cylinder was substituted for the small cylinder.

2.1.3.2. Endpoint condition

2.1.3.2.4. Habituation event. The habituation event shown in the endpoint condition was identical to that in the midpoint condition except that, as in the test events, the bug traveled to the end rather than to the middle of the track.

2.1.3.3. Small- and large-cylinder test events. The small- and large-cylinder test events shown in the endpoint condition were identical to those in the midpoint condition.[3]

2.1.4. Procedure

Prior to the beginning of the experiment, each infant was shown the three cylinders and the two gloves for a few minutes while the parent filled out consent forms. During the experiment, the infant sat on the parent's lap in front of the apparatus, facing the middle of the track. The infant's head was approximately 80 cm from the track. The parent was asked not to interact with the infant while the experiment was in progress, and to close his or her eyes during the test trials.

The infant's looking behavior was monitored by two observers who watched the infant through peepholes in the cloth-covered frames on either side of the apparatus. Each observer held a button connected to a DELL computer and depressed the button when the infant attended to the events. Each trial was divided into 100-ms intervals, and the computer determined in each interval whether the two observers agreed on the direction of the infant's gaze. Interobserver agreement was calculated for each test trial on the basis of the number of intervals in which the computer registered agreement, out of the total number of intervals in the trial. Agreement averaged 96% per trial per infant.

The looking times recorded by the primary observer were used to determine when a trial had ended (see below). Because observers could determine from available

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[3] Because the bug traveled at the same speed whenever it rolled to the end of the track, many of the test events involved speed violations. Thus, (a) the bug traveled faster than it should have in the small-cylinder event shown in the midpoint and endpoint conditions and (b) the bug traveled slower than it should have in the large-cylinder event shown in the endpoint condition. Indeed, the only event in which no speed violation occurred was the large-cylinder event shown in the midpoint condition, in which the bug traveled both farther and faster than in the habituation event. However, even adult subjects appeared impervious to these speed violations (Kotovsky and Baillargeon, 1994). This finding was not unexpected since the speed traveled by the bug across trials was more difficult to remember than its distance.

sound cues in each trial (a) which cylinder was used and (b) how far the bug rolled, special steps were taken to ensure that the primary observer was blind during the test-trials to the condition (midpoint or endpoint) to which the infant was assigned. Specifically, different primary observers were used to monitor the infant's looking times during the habituation and test trials; the test trials primary observer was not present in the experimental room during the habituation trials and hence could not be cued to the infant's condition by the sounds that accompanied the bug's displacement. Furthermore, all of the experiments reported in this paper, although described sequentially, were in fact conducted simultaneously, together with additional experiments discussed elsewhere (e.g. Kotovsky, 1994; L. Kotovsky and R. Baillargeon, unpublished data); as a result, observers were often blind to the infant's experiment as well as condition.

During the habituation phase of the experiment, the infants in the midpoint and endpoint conditions saw the habituation event appropriate for their condition on successive trials. Each trial ended when the infant either (a) looked away from the event for 2 consecutive seconds after looking at it for at least 7 cumulative seconds, beginning at the end of the pretrial, when the cylinder was placed at the top of the ramp or (b) looked at the event for 60 cumulative seconds without looking away for 2 consecutive seconds. Trials continued until the infant (a) satisfied a criterion of habituation of a 50% or greater decrease in looking time on three consecutive trials, relative to the infant's looking time on the first three trials, or (b) completed nine habituation trials. Therefore, the minimum number of habituation trials an infant could receive was six and the maximum number was nine. Of the 32 infants in the experiment, 16 (two males and six females in the midpoint condition, and four males and four females in the endpoint condition) completed nine habituation trials without satisfying the habituation criterion; the remaining 16 infants (five males and three females in the midpoint condition, and four males and four females in the endpoint condition) took a mean of 7.1 trials to reach the criterion.

After the habituation phase, the infants were presented with the small- and large-cylinder events on alternate trials until they completed three pairs of test trials. Half of the infants in each condition saw the small-cylinder event first and half saw the large-cylinder event first. The criteria used to determine the end of the test trials were the same as for the habituation trials. The 7-s value for the minimum length of each trial was selected to ensure that the infants had the opportunity to notice how far the bug rolled in each trial.

Three of the 32 infants in the experiment failed to complete the full complement of three pairs of test trials. These infants completed only two pairs, two because of apparatus failure and one because of fussiness. All subjects (in this experiment as well as in the next experiments) were included in the data analyses, whether they had completed three or only two pairs of test trials. Preliminary analyses revealed no significant effect of sex on the looking times of the infants in the two conditions at the habituation (all $F < 0.80$) and test events (all $F < 0.69$); the data were therefore collapsed across this factor in subsequent analyses.

2.2. Results

2.2.1. Habituation trials

The infants' looking times during the last six habituation trials (see Fig. 2) were analyzed by means of a 2 × 6 mixed-model analysis of variance (ANOVA) with Condition (midpoint or endpoint condition) as a between-subjects factor and Trial (1–6) as a within-subject factor. The analysis yielded a significant main effect of Trial, $F(5, 150) = 12.02$, $P < 0.0001$, indicating that the infants looked reliably less across trials. The main effect of Condition was not significant, $F(1, 30) = 1.85$, $P > 0.05$, nor was the Condition × Trial interaction, $F(5, 150) = 1.70$, $P > 0.05$, indicating that the infants in the midpoint and endpoint conditions did not differ reliably in their responses to the habituation events.

2.2.2. Test trials

Fig. 2 presents the infants' mean looking times at the test events. It can be seen that

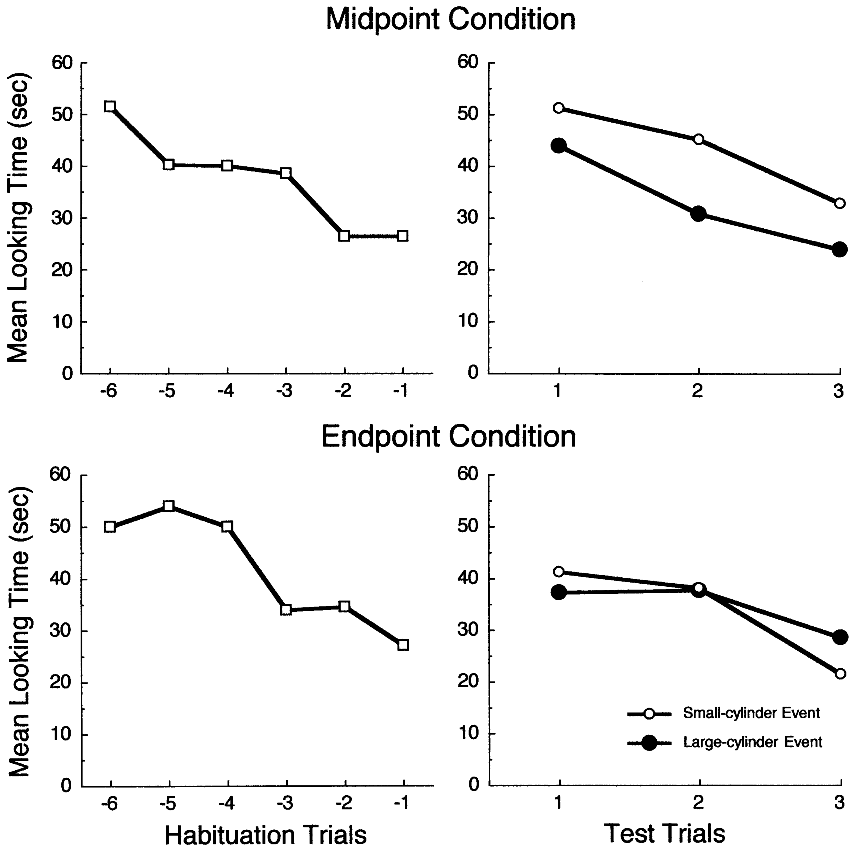

Fig. 2. Mean looking times of the 6.5-month-old infants in the midpoint and endpoint conditions of Experiment 1 at the habituation and test events.

the infants in the midpoint condition looked longer at the small- than at the large-cylinder test event, whereas the infants in the endpoint condition tended to look equally at the two events.

The infants' looking times were analyzed by means of a $2 \times 2 \times 2 \times 3$ mixed-model ANOVA with Condition (midpoint or endpoint condition) and Order (small- or large-cylinder event first) as between-subjects factors and with Event (small- or large-cylinder event) and Test Pair (first, second, or third pair of test trials) as within-subject factors. Because the design was unbalanced, the SAS GLM procedure was used to calculate the ANOVA (SAS Institute, 1992). The analysis revealed a significant Condition × Event interaction, $F(1, 134) = 4.19$, $P < 0.05$. Planned comparisons indicated that the infants in the midpoint condition looked reliably longer at the small- ($M = 43.1$, SD = 20.5) than at the large- ($M = 32.9$, SD = 20.7) cylinder event, $F(1, 134) = 7.18$, $P < 0.01$, whereas the infants in the endpoint condition tended to look equally at the two events, $F(1, 134) = 0.02$ (small-cylinder event: $M = 34.4$, SD = 20.8; large-cylinder event: $M = 34.9$, SD = 21.2). Inspection of the infants' individual looking patterns yielded similar results (see Fig. 3): whereas 12 of the 16 infants in the midpoint condition looked longer at the small- than at the

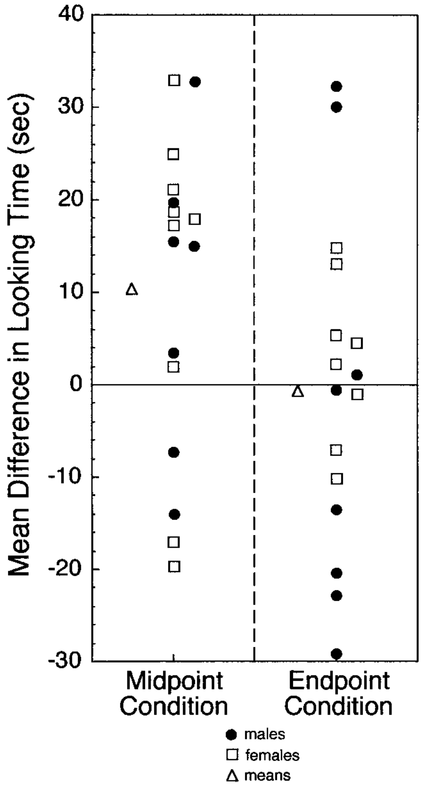

Fig. 3. Differences in mean looking times of the 6.5-month-old infants in the midpoint and endpoint conditions of Experiment 1 at the small- and large-cylinder test events. Each dot represents an individual infant.

large-cylinder event (cumulative binomial probability $P < 0.05$), only eight of the 16 infants in the endpoint condition did so ($P > 0.05$).

The ANOVA also revealed a significant main effect of Test Pair, $F(2, 134) = 11.59$, $P < 0.0001$, indicating that the infants looked reliably less as the experiment progressed. Finally, there was a significant Order × Event interaction, $F(1, 134) = 6.53$, $P < 0.05$. Although the infants in the two order conditions did not differ in their responses to the large-cylinder event (small-cylinder event first: $M = 32.2$, SD = 20.2; large-cylinder event first: $M = 35.6$, SD = 21.6, $F(1, 134) = 0.74$), the infants who saw the small-cylinder event first looked reliably longer at it ($M = 44.1$, SD = 19.1) than did the infants who saw the large-cylinder event first ($M = 33.6$, SD = 21.7), $F(1, 134) = 7.47$, $P < 0.01$. Because neither of the interactions involving Condition as well as Order and Event was significant (Condition × Order × Event, $F(1, 134) = 0.34$; Condition × Order × Event × Pair, $F(2, 134) = 0.98$), the interaction between Order and Event has no bearing on the present hypotheses and will not be discussed further.

2.3. Discussion

The infants in the midpoint condition looked reliably longer at the small- than at the large-cylinder event, whereas the infants in the endpoint condition tended to look equally at the two events. These results suggest that the 6.5-month-olds in Experiment 1 (a) believed that the size of the cylinder should affect the length of the bug's trajectory and (b) used the habituation event to calibrate their expectations about the test events. After watching the medium cylinder propel the bug to the middle of the track, the infants were surprised to see the small but not the large cylinder propel the bug to the end of the track. However, after observing the medium cylinder propel the bug to the end of the track, the infants were not surprised to see the bug do the same with either the small or the large cylinder.

The pattern of results produced by the 6.5-month-olds in Experiment 1 was thus analogous to that produced by the 11-month-olds in our initial experiment (Kotovsky and Baillargeon, 1994). Experiment 2 attempted to extend these findings to younger infants: 5.5-month-old infants were tested with the midpoint condition procedure used in Experiment 1. Only the midpoint condition procedure was used, because pilot data suggested that the younger infants in Experiment 2 might perform more poorly then the older infants in Experiment 1, and only in the midpoint condition did these older infants produce reliably different looking times at the small- and large-cylinder test events.

3. Experiment 2

3.1. Method

3.1.1. Subjects

The subjects were 27 healthy, full-term infants ranging in age from 4 months, 29 days to 6 months, 6 days ($M = 5$ months, 17 days). There were 13 males ($M = 5$ months, 18 days) and 14 females ($M = 5$ months, 16 days). An additional 11 infants were tested but eliminated, six because of apparatus failure, three because they looked the maximum number of seconds allowed on five or more test trials, one because of fussiness, and one because of procedural problems.

3.1.2. Apparatus, events, and procedure

The apparatus, events, and procedure in Experiment 2 were identical to those of the midpoint condition in Experiment 1. Of the 27 infants in the experiment, 20 (nine males and 11 females) completed nine habituation trials without satisfying the habituation criterion; the remaining seven infants (four males and three females) took an average of 7.4 trials to reach the criterion. During the test trials, 13 infants saw the small-cylinder event first and 14 saw the large-cylinder event first. One infant completed only two test pairs, because of fussiness. Interobserver agreement during the test trials averaged 95% per trial per infant.

Preliminary analyses indicated that, contrary to what had been found in Experiment 1, sex had a significant effect on the infants' looking times at the test events; this factor was therefore retained in the analyses.

3.2. Results

3.2.1. Habituation trials

The infants' looking times during the last six habituation trials (see Fig. 4) were analyzed by means of a 2 × 6 mixed-model ANOVA with Sex as a between-subjects factor and Trial (1–6) as a within-subject factor. The analysis revealed a significant main effect of Trial, $F(5, 125) = 3.96$, $P < 0.0025$, indicating that the infants looked reliably less across trials. Neither the main effect of Sex, $F(1, 25) = 0.09$, nor the Sex × Trial interaction, $F(5, 125) = 1.46$, $P > 0.05$, was significant, suggesting that the male and female infants did not differ reliably in their responses to the habituation event.

3.2.2. Test trials

Fig. 4 presents the infants' mean looking times at the test events. It can be seen that, like the 6.5-month-olds in Experiment 1, the female infants looked longer at the small- than at the large-cylinder event; in contrast, the male infants tended to look equally at the events.

The infants' looking times were analyzed by means of a $2 \times 2 \times 2 \times 3$ ANOVA with Sex and Order (small- or large-cylinder event first) as between-subjects factors and with Event (small- or large-cylinder event) and Test Pair (first, second, or third pair of test trials) as within-subject factors. There was a significant main effect of Event, $F(1, 68) = 6.03$, $P < 0.025$, and a significant Sex × Event interaction, $F(1, 68) = 5.73$, $P < 0.025$. Follow-up comparisons indicated that the female infants looked reliably longer at the small- ($M = 42.9$, $SD = 19.4$) than at the large- ($M = 30.4$, $SD = 19.8$) cylinder event, $F(1, 68) = 11.90$, $P < 0.001$, whereas the male infants tended to look equally at the two events, $F(1, 68) = 0.03$ (small-cylin-

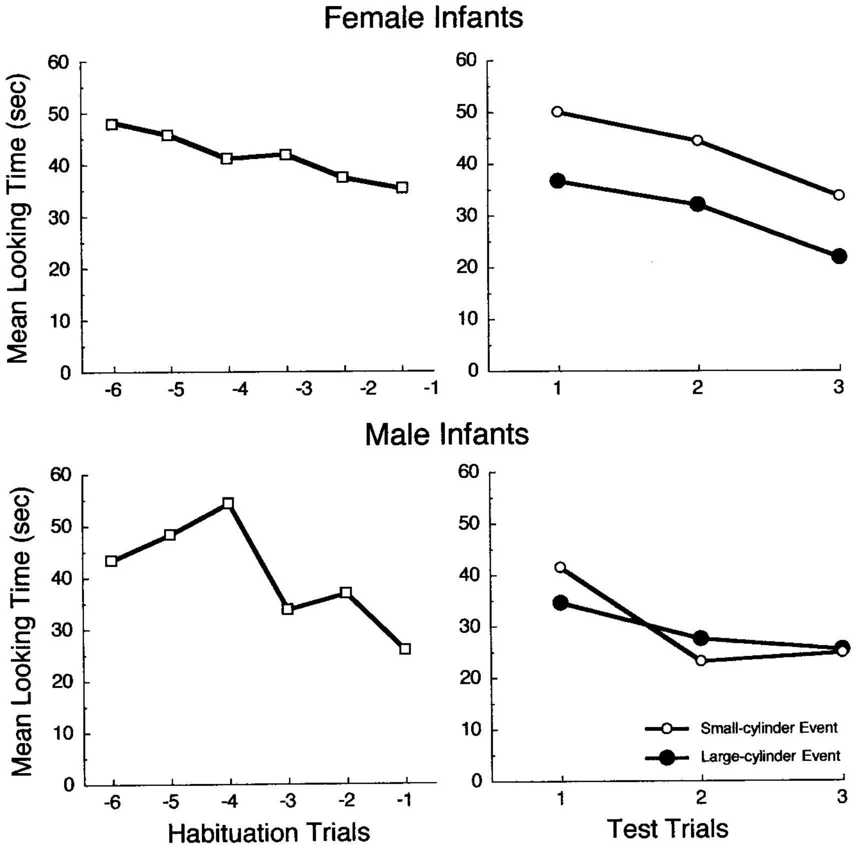

Fig. 4. Mean looking times of the 5.5-month-old female and male infants in Experiment 2 at the habituation and test events.

der event, $M = 29.8$, SD = 19.9; large-cylinder event, $M = 29.2$, SD = 20.7). Examination of the infants' individual looking patterns (see Fig. 5) yielded similar results: whereas 11 of the 14 female infants looked longer at the small- than at the large-cylinder event (cumulative binomial probability $P < 0.05$), only six of the 13 male infants did so ($P > 0.05$).

The ANOVA also yielded a significant main effect of Test Pair, $F(2, 45) = 5.81$, $P < 0.01$, indicating that the infants looked reliably less as the experiment progressed.

3.3. Discussion

The responses of the male and female infants in Experiment 2 to the midpoint condition test events were reliably different: whereas the female infants looked significantly longer at the small- than at the large-cylinder event, the male infants tended to look equally at the events. This sex difference was not entirely unexpected: as was alluded to in Section 1, a number of experiments from our laboratory have

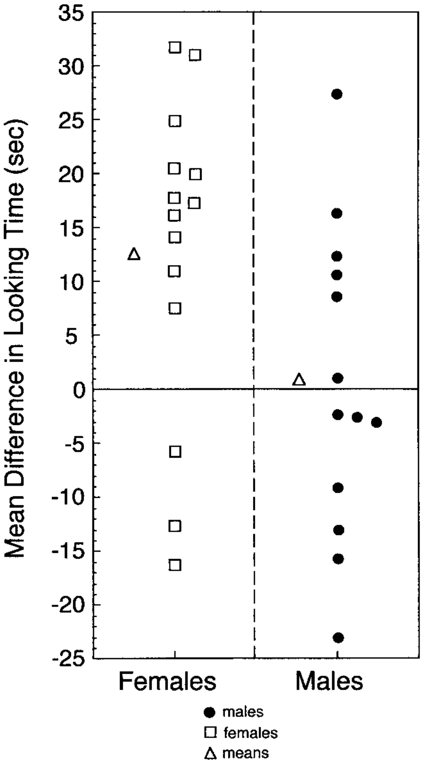

Fig. 5. Differences in mean looking times of the 5.5-month-old female and male infants in Experiment 2 at the small- and large-cylinder test events. Each dot represents an individual infant.

shown that females sometimes precede males by a few weeks in their development (e.g. Baillargeon and DeVos, 1991; R. Baillargeon, H. Raschke, and A. Needham, unpublished data), and similar findings have been reported by investigators from other laboratories (e.g. Bauer et al., 1986; Gwiazda et al., 1989a; Gwiazda et al., 1989b; Streri et al., 1996).[4]

[4] It might be suggested that the sex difference observed in Experiment 2 was perhaps due to some other difference in the infants' responses, such as how well they encoded and remembered the habituation event. There is evidence in the physical-reasoning literature that infants who are fast habituators sometimes perform better than do infants who are slow habituators (e.g. Baillargeon, 1987). Accordingly, the responses of the infants in Experiment 2 who habituated to the midpoint event in nine trials or fewer (four males and three females; fast habituators) were compared to those of the infants who did not (nine males and 11 females; slow habituators). The infants' looking times were analyzed by means of a 2 × 2 × 3 ANOVA with Habituation Performance (fast or slow habituators) as a between-subjects factor, and with Event (small- or large-cylinder event) and Test Pair (first, second, or third pair of test trials) as within-subject factors. The Habituation Performance × Event interaction was not significant, $F(1, 74) = 0.31$, indicating that the fast and slow habituators did not differ reliably in their responses to the test events (fast habituators: small-cylinder event, $M = 29.6$, SD = 20.8, large-cylinder event, $M = 30.1$, SD = 23.1; slow habituators: small-cylinder event, $M = 35.8$, SD = 19.5, large-cylinder event, $M = 32.8$, SD = 20.8. The only significant effect was that of test pair, $F(2, 74) = 10.68$, $P < 0.001$, indicating that the infants looked reliably less as the experiment progressed.

To shed further light on the sex effect observed in Experiment 2, additional data were collected with female infants in Experiment 2A and with male infants in Experiments 2B and 2C.

4. Experiment 2A

The most likely interpretation for the results obtained with the 5.5-month-old female infants in Experiment 2 was that these infants, like the 6.5-month-old male and female infants in Experiment 1, (a) believed that the size of the cylinder affected the length of the bug's trajectory and (b) were able to engage in calibration-based reasoning about this size/distance relation. However, another interpretation of the results of Experiment 2 was that the female infants found the small cylinder intrinsically more attractive than the large cylinder. Although unlikely, this alternative interpretation still needed to be ruled out. Accordingly, an additional group of 5.5-month-old female infants was tested with the endpoint condition procedure used in Experiment 1. We reasoned that if the female infants in Experiment 2 simply preferred the small over the large cylinder, then the female infants in Experiment 2A should also look reliably longer at the small- than at the large-cylinder test event. However, if the females in Experiment 2 detected the size/distance violation in the small-cylinder event, then the females in Experiment 2A should look equally at the two test events, because neither event presented such a violation.

4.1. Method

4.1.1. Subjects

The subjects were 11 healthy, full-term female infants ranging in age from 5 months, 1 day to 5 months, 29 days ($M = 5$ months, 13 days). An additional three infants were tested but eliminated, one because of apparatus failure, one because of fussiness, and one because she looked the maximum number of seconds allowed on all six test trials.

4.1.2. Apparatus, events and procedure

The apparatus, events, and procedure in Experiment 2A were identical to those of the endpoint condition in Experiment 1. Of the 11 infants in the experiment, nine completed nine habituation trials without satisfying the habituation criterion; the remaining two infants took an average of 8.0 trials to reach the criterion. During the test trials, five infants saw the small-cylinder event first, and six saw the large-cylinder event first. One infant failed to contribute the full complement of three test pairs to the data analyses; this infant completed only two test pairs, because of apparatus failure. Interobserver agreement during the test trials averaged 95% per trial per infant.

4.2. Results

4.2.1. Habituation trials

For purposes of comparison, the looking times of the 5.5-month-old female infants in Experiments 2 and 2A were analyzed with those of the 6.5-month-old male and female infants in Experiment 1. The infants' looking times on the last six habituation trials were analyzed by means of a $3 \times 2 \times 6$ mixed-model ANOVA with Group (6.5-month-old males, 6.5-month-old females, or 5.5-month-old females) and Condition (midpoint or endpoint condition) as between-subjects factors and with Trial (1–6) as a within-subject factor. The only significant effect was that of Trial, $F(5, 255) = 15.31$, $P < 0.0001$, indicating that the infants looked reliably less across trials. The main effect of Group was not significant, $F(2, 51) = 0.77$, nor were any of the interactions involving this factor, all F's < 0.75, indicating that the three groups of infants did not differ reliably in their responses to the midpoint and endpoint habituation events.

4.2.2. Test trials

Fig. 6 presents the mean looking times of the 6.5-month-old male infants, 6.5-month-old female infants, and 5.5-month-old female infants at the test events. It can be seen that in each group the infants in the midpoint condition preferred the small- over the large-cylinder event, whereas the infants in the endpoint condition showed no preference for either event.

The infants' looking times were compared by means of a $3 \times 2 \times 2 \times 2 \times 3$ ANOVA with Group (6.5-month-old males, 6.5-month-old females, or 5.5-month-old females), Condition (midpoint or endpoint condition), and Order (small- or large-cylinder event first) as between-subjects factors and with Event (small- or large-cylinder event) and Test Pair (first, second, or third pair of test-trials) as within-subject factors. The analysis yielded a significant main effect of Event, $F(1, 215) = 5.43$, $P < 0.025$, and a significant Condition × Event interaction, $F(1, 215) = 5.97$, $P < 0.025$. Planned comparisons confirmed that the infants in the midpoint condition looked reliably longer at the small- ($M = 43.0$, SD = 19.9) than at the large- ($M = 31.8$) cylinder event, $F(1, 215) = 14.94$, $P < 0.00025$, whereas the infants in the endpoint condition tended to look equally at the events, $F(1, 215) = 0.02$ (small-cylinder event, $M = 34.4$, SD = 20.0; large-cylinder event, $M = 33.9$, 20.6). The main effect of Group was not significant, $F(2, 45) = 0.29$, nor were any of the interactions involving this factor, all F's < 1.34, $P > 0.05$, confirming that the three groups of infants did not differ reliably in their responses to the midpoint and endpoint test events.

The ANOVA also yielded a significant main effect of Test Pair, $F(2, 215) = 13.78$, $P < 0.0001$, indicating that the infants looked reliably less as the experiment progressed. Finally, as in Experiment 1, the analysis revealed a significant Order × Event interaction, $F(1, 215) = 5.12$, $P < 0.025$: although the infants in the two order conditions tended to look equally at the large-cylinder event (small-cylinder event first: $M = 31.9$, SD = 20.2; large-cylinder event first: $M = 33.5$, SD = 20.6; $F(1, 215) = 0.55$), the infants who saw the small-cylinder event first

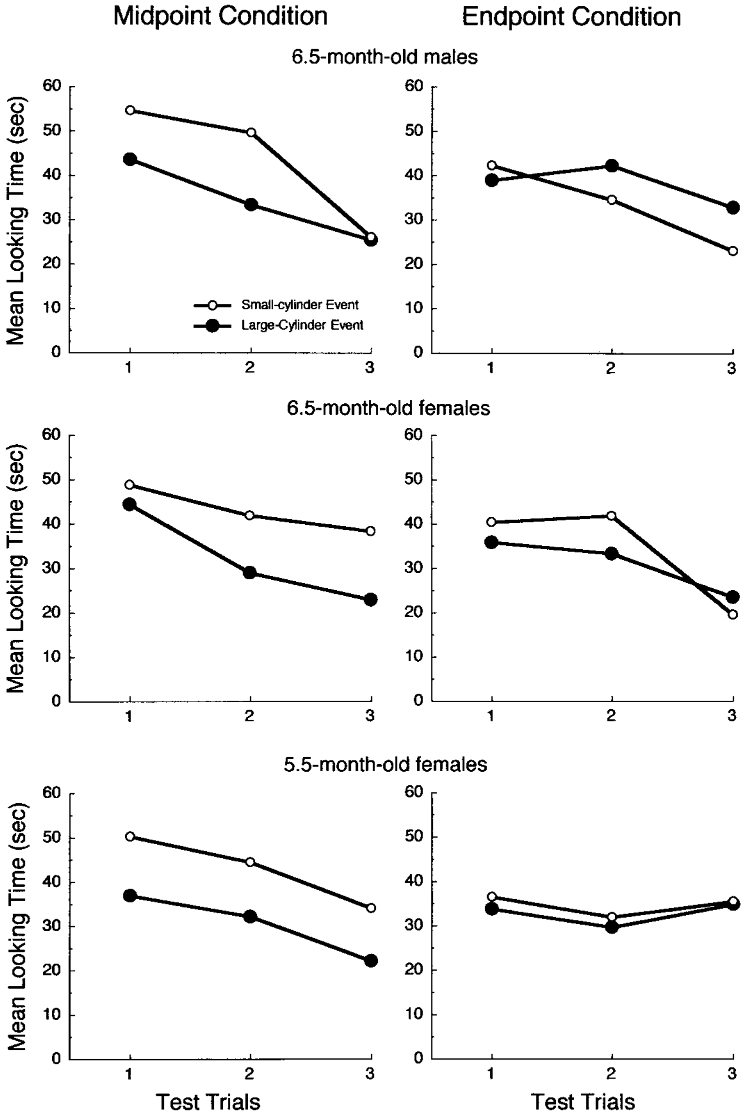

Fig. 6. Mean looking times of the 6.5-month-old female and male infants and the 5.5-month-old female infants in the midpoint and endpoint conditions of Experiments 1, 2 and 2A at the small- and large-cylinder test events.

looked reliably longer at it ($M = 42.4$, SD = 18.8) than did the infants who saw the large-cylinder event first ($M = 36.0$, SD = 21.3), $F(1, 215) = 4.42$, $P < 0.05$. Because none of the interactions involving Condition as well as Order and Event were significant (all F's < 1.21, $P > 0.05$), the interaction between Order and Event does not bear on the present theoretical issues and will not be discussed further.

4.3. Discussion

Like the 6.5-month-old infants in Experiment 1, the 5.5-month-old female infants in Experiments 2 and 2A showed a reliable preference for the small- over the large-cylinder test event in the midpoint but not the endpoint condition. Together, the results of Experiments 1, 2, and 2A thus confirm and extend those of our previous experiment with 11-month-old infants (Kotovsky and Baillargeon, 1994). Specifically, the present results suggest that, by 5.5 to 6.5 months of age, infants already (a) are aware that, in a collision event between a moving and a stationary object, the size of the moving object affects the distance traveled by the stationary object and (b) are able to engage in calibration-based reasoning about this size/distance relation.

Although the present results are generally similar to those of our previous experiment (Kotovsky and Baillargeon, 1994), one difference may be worth noting. This difference has to do with the persistence of the infants' responses to the test events. The 6.5-month-old infants and 5.5-month-old female infants tested in the midpoint condition in the present research showed a sizable preference for the small- over the large-cylinder event on the first (small, $M = 50.7$, SD = 16.7; large, $M = 40.5$, SD = 19.4), second (small, $M = 44.8$, SD = 18.0; large, $M = 31.4$, SD = 20.7), and third (small, $M = 33.3$, SD = 21.3; large, $M = 23.1$, SD = 17.1) pair of test-trials. In contrast, pilot data collected with 10- to 12-month-old infants in the same condition revealed that these older infants showed a marked preference for the small- over the large-cylinder event only on the first test trial (these data led to the adoption of the single test trial procedure in Kotovsky and Baillargeon, 1994).

Why did the response of the younger infants to the small-cylinder event persist across trials, and that of the older infants rapidly dissipate? At least two explanations are possible. One has to do with the fact that the younger infants saw the medium-cylinder event for 6-9 habituation trials, whereas the older infants saw this event for only three familiarization trials; as a result, the older infants may have been less reluctant to revise their initial expectation about the small-cylinder event in the face of inconsistent evidence. A second, more intriguing explanation is that the older infants possessed additional knowledge that enabled them to more readily accept the small-cylinder event (e.g. Baillargeon, 1994b). For example, the older infants might have been aware that the mass, rather than the size, of the cylinders was the variable that mattered and they might have inferred (as did some adult subjects; see Kotovsky and Baillargeon, 1994) that (a) the cylinders' masses were not proportional to their sizes and (b) the small cylinder was sufficiently heavy to propel the bug to the end of the track. We return in Section 7 to issues concerning the development of infants' knowledge about collision events.

5. Experiment 2B

The results obtained in the midpoint condition with the 6.5-month-old male and female infants in Experiment 1 and the 5.5-month-old female infants in Experiment 2 were remarkably consistent: the infants all looked reliably longer at the small- than at the large-cylinder test event. In marked contrast, the 5.5-month-old male infants in Experiment 2 tended to look equally at the two test events. How should this negative finding be interpreted? At least three explanations were possible. One was that the young male infants had not yet learned that when a moving and a stationary object collide, the size of the moving object can be used to reason about the length of the stationary object's displacement. A second possibility was that the young male infants were aware of this relation, but could not engage in calibration-based reasoning about it. Yet another hypothesis was that the young male infants possessed both the knowledge and calibration-based reasoning ability necessary to succeed at the present task, but were prevented from doing so because they lacked some of the information necessary to calibrate their predictions about the test events. In particular, the infants might have had difficulty remembering how far the bug rolled when hit by the medium cylinder, making it impossible for them to predict how far the bug should roll when hit by the small and large cylinders.

Experiment 2B was designed to examine this last hypothesis: it tested 5.5-month-old male infants' ability to encode and remember the length of the bug's trajectory. As in Experiment 1, the infants were habituated to the medium cylinder hitting the bug and propelling it to either the middle (midpoint condition) or the end (endpoint condition) of the track. Following habituation, the infants saw both of these events on alternate test trials; the infants thus saw the bug roll to the same location as in the habituation event in one test event (familiar event) and to a novel location in the other test event (novel event). We reasoned that evidence that the infants in Experiment 2B looked reliably longer at the novel than at the familiar test event would rule out the hypothesis that the 5.5-month-old male infants in Experiment 2 looked equally at the small- and large-cylinder test events because they could not remember how far the bug rolled during the habituation event and hence had no basis for calibrating their predictions about the test events.

5.1. Method

5.1.1. Subjects

The subjects were 16 healthy, full-term male infants ranging in age from 5 months, 1 day to 6 months, 4 days (*M* = 5 months, 19 days). Half of the infants were assigned to the midpoint condition (*M* = 5 months, 21 days) and half to the endpoint condition (*M* = 5 months, 16 days). An additional seven infants were tested but eliminated, two because of fussiness, two because of apparatus failure, two because they looked the maximum number of seconds allowed on five or more test trials, and one because of procedural error.

5.1.2. Apparatus, events, and procedure

The apparatus and stimuli in Experiment 2B were identical to those in the preceding experiments except that only the medium blue cylinder was used. The infants in the midpoint condition were habituated to the same event as the infants in the midpoint condition in Experiments 1 and 2, and the infants in the endpoint condition were habituated to the same event as the infants in the endpoint condition in Experiments 1 and 2A. Following habituation, all infants saw these same two events on alternate test trials. Of the 16 infants in Experiment 2B, six completed nine habituation trials without satisfying the habituation criterion; the other ten infants took a mean of 7.2 trials to reach the criterion. One infant completed only two test pairs, because of fussiness. Interobserver agreement during the test trials averaged 95% per trial per infant.

5.2. Results

5.2.1. Habituation Trials

The infants' looking times at the last six habituation trials (see Fig. 7) were analyzed as in Experiment 1. The analysis revealed a significant main effect of trial, $F(5, 70) = 11.97$, $P < 0.0001$, indicating that the infants looked reliably less as the habituation trials progressed. The main effect of Condition was not significant, $F(1, 14) = 1.66$, $P > 0.05$, nor was the Condition × Trial interaction, $F(5, 70) = 1.90$, $P > 0.05$, indicating that the infants in the midpoint and endpoint conditions did not differ reliably in their responses to the habituation events.

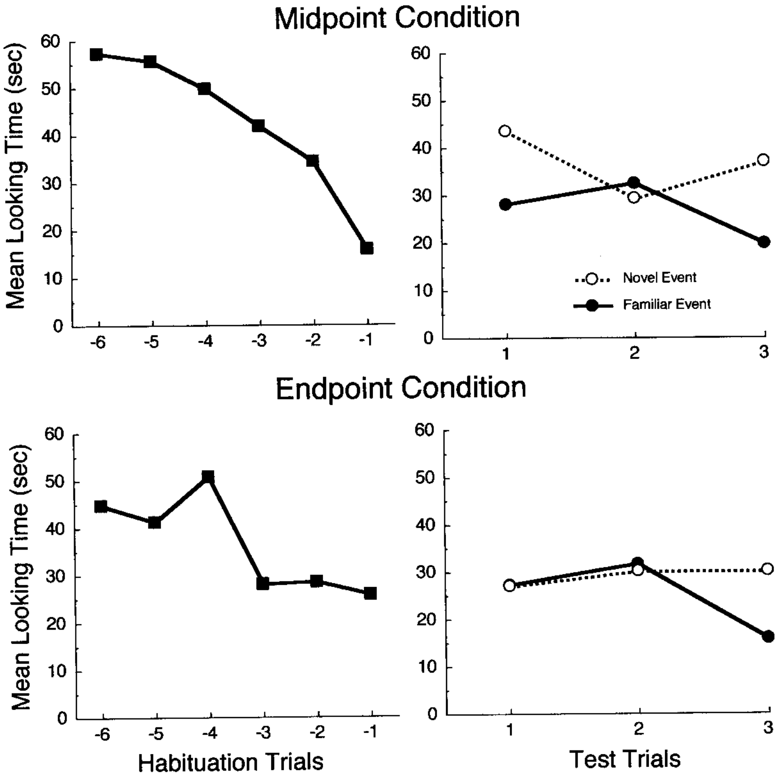

Fig. 7. Mean looking times of the 5.5-month-old male infants in the midpoint and endpoint conditions of Experiment 2B at the habituation and test events.

5.2.2. Test trials

Fig. 7 presents the infants' mean looking times at the test events. It can be seen that the infants in the midpoint and endpoint conditions looked longer overall at the novel than at the familiar event.

The infants' looking times were analyzed by means of a 2 × 2 × 2 × 3 mixed-model ANOVA with Condition (midpoint or endpoint condition) and Order (novel or familiar event first) as between-subjects factors and with Event (novel or familiar event) and Test Pair (first, second, or third pair of test trials) as within-subject factors. The analysis revealed a significant main effect of Event, $F(1, 35) = 5.82$, $P < 0.025$, indicating that the infants looked reliably longer overall at the novel ($M = 32.9$, $SD = 19.9$) than at the familiar ($M = 26.0$, $SD = 16.6$) event. The main effect of Condition was not significant, $F(1, 12) = 1.23$, $P > 0.05$, nor was any of the interactions involving Condition and Event, all F's < 1.19, $P > 0.05$, indicating that the infants in the midpoint and endpoint Conditions did not differ reliably in their responses to the novel and familiar events.

Examination of the infants' individual looking patterns (see Fig. 8) revealed

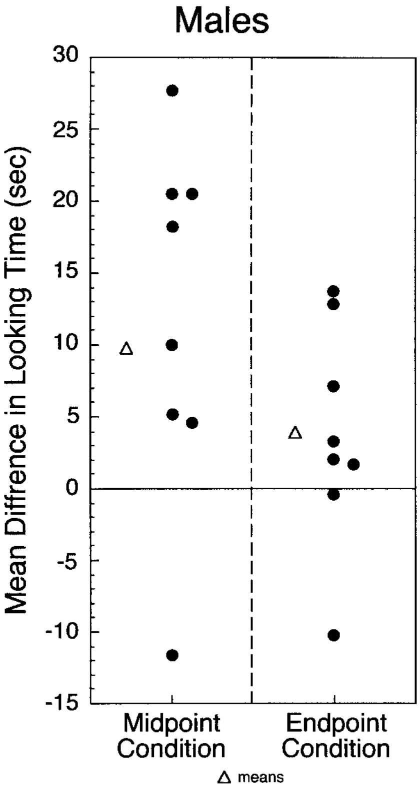

Fig. 8. Differences in mean looking times of the 5.5-month-old male infants in the midpoint and endpoint conditions of Experiment 2B at the novel and familiar test events. Each dot represents an individual infant.

a similar pattern: overall, 13 of the 16 infants in the experiment looked longer at the novel than at the familiar event (cumulative binomial probability $P < 0.025$).

5.3. Discussion

The 5.5-month-old male infants in Experiment 2B looked reliably longer at the novel than at the familiar test event, indicating that they (a) remembered how far the bug rolled in the habituation event and (b) detected that the bug traveled to a new location in the novel but not the familiar event. These results provide evidence against the hypothesis that the 5.5-month-old male infants in Experiment 2 could not remember how far the bug rolled when hit by the medium cylinder and hence lacked the information they needed to calibrate their predictions about the small and large cylinders.

If the young male infants in Experiment 2 were capable of remembering how far the bug rolled in the habituation event, why did they look equally at the small- and large-cylinder test events? Two possible explanations were mentioned earlier. One was that the infants had not yet learned that, when a moving and a stationary object collide, the size of the moving object can be used to reason about the distance traveled by the stationary object. The second possibility was that the infants were aware of this size/distance relation, but lacked the ability to engage in calibration-based reasoning about this or any other relation.

Experiment 2C was designed to examine the second of these hypotheses: it tested 5.5-month-old male infants’ ability to use information about how far the bug rolled when hit by the medium blue cylinder to calibrate their predictions about how far the bug should roll when hit by two novel cylinders. As in the midpoint condition in Experiments 1 and 2, the infants were habituated to the medium blue cylinder hitting the bug and propelling it to the middle of the track. Following habituation, the infants again saw an orange and a yellow cylinder propel the bug to the end of the track. The only difference with Experiments 1 and 2 was that the test cylinders were both equal in size to the habituation cylinder, rather than being smaller or larger.

Our reasoning was as follows. If the infants in Experiment 2C (a) possessed an expectation that same-size cylinders should have similar effects and (b) were able to use the habituation event to calibrate their predictions about the test events, then they should expect the medium orange and yellow cylinders to propel the bug to the middle of the track, and they should be surprised when this expectation was violated. The infants should therefore produce equal and *high* looking times at the orange- and yellow-cylinder test events, in marked contrast with the equal and *low* looking times produced by the male infants in Experiment 2 at the small- and large-cylinder test events. Such results, we reasoned, would provide evidence against the hypothesis that the male infants in Experiment 2 failed to show a reliable preference for the small-cylinder event because they could not engage in calibration-based reasoning about the habituation and test events.

6. Experiment 2C

6.1. Method

6.1.1. Subjects

The subjects were 16 healthy, full-term male infants ranging in age from 4 months, 29 days to 5 months, 27 days (M = 5 months, 14 days). An additional seven infants were tested but eliminated, two because of apparatus failure, two because of fussiness, two because of procedural error, and one because he looked the maximum number of seconds allowed on all test trials.

6.1.2. Apparatus, events and procedure

The apparatus, events, and procedure in Experiment 2C were identical to those of the midpoint condition in Experiments 1 and 2, with one exception: the small orange and the large yellow cylinders were replaced with a medium orange and a medium yellow cylinder. As in Experiments 1 and 2, both novel cylinders propelled the bug to the end of the track. Of the 16 infants in Experiment 2C, 13 completed nine habituation trials without satisfying the habituation criterion; the remaining three infants took an average of 6.3 trials to reach the criterion. During the test trials, half of the infants saw the orange-cylinder event first, and half saw the yellow-cylinder event first. Interobserver agreement during the test trials averaged 96% per trial per infant.

6.2. Results

6.2.1. Habituation Trials

The looking times of the infants in Experiment 2C during the last six habituation trials (see Fig. 9) were compared to those of the male infants in Experiment 2. These data were analyzed by means of a 2 × 6 mixed-model ANOVA with Experiment (2 or 2C) as a between-subjects factor and with Trial (1–6) as a within-subject factor. The analysis revealed a significant main effect of Trial, $F(5, 135) = 8.22$, $P < 0.001$, indicating that the infants looked reliably less across trials. Neither the main effect of Experiment, $F(1, 27) = 0.98$, nor the Experiment × Trial interaction, $F(5, 135) = 0.54$, was significant, suggesting that the infants in Experiments 2 and 2C did not differ reliably in their responses to the habituation event.

6.2.2. Test trials

Fig. 9 presents the mean looking times at the orange- and yellow-cylinder test events of the infants in Experiment 2C.

The looking times of the male infants in Experiments 2 and 2C were compared by means of a 2 × 2 × 2 × 3 mixed-model ANOVA with Experiment (2 or 2C) and Order (small/orange-cylinder or large/yellow-cylinder event first) as between-subjects factors and with Event (small/orange-cylinder or large/yellow-cylinder event) and Test Pair (first, second, or third pair of test-trials) as within-subject factors.

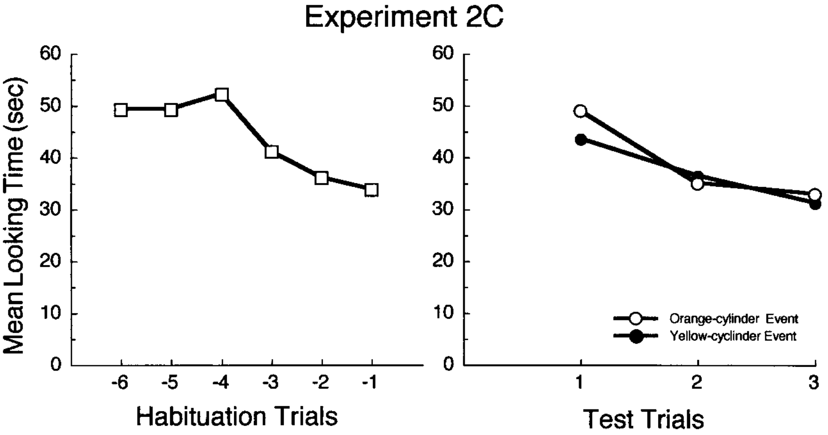

Fig. 9. Mean looking times of the 5.5-month-old male infants in Experiment 2C at the habituation and test events.

There was a significant main effect of Experiment, $F(1, 25) = 6.61$, $P < 0.05$, indicating that the infants in Experiment 2 looked reliably longer overall ($M = 38.6$, SD = 20.9) than did those in Experiment 2C ($M = 29.5$, SD = 20.2). Planned comparisons further revealed that (a) the infants in Experiment 2C looked reliably longer at the orange-cylinder event ($M = 39.5$, SD = 21.3) than the infants in Experiment 2 looked at the small-cylinder event ($M = 29.8$, SD = 19.9), $F(1, 125) = 5.44$, $P < 0.05$; and (b) the infants in Experiment 2C looked reliably longer at the yellow-cylinder event ($M = 37.7$, SD = 20.6) than the infants in Experiment 2 looked at the large-cylinder event ($M = 29.2$, SD = 20.6), $F(1, 125) = 4.13$, $P < 0.05$.

The analysis also revealed a significant main effect of Test Pair, $F(2, 125) = 8.19$, $P < 0.001$, indicating that the infants looked reliably less across test pairs.

6.2.3. Further analyses

In a final series of analyses, the looking times of the infants in Experiment 2C were compared to those of the infants in the midpoint condition in Experiment 2B. First, the infants' looking times during the last six habituation trials were analyzed in the same manner as the habituation data of Experiments 2 and 2C. The analysis revealed a significant main effect of Trial, $F(5, 110) = 7.00$, $P < 0.01$, indicating that the infants looked reliably less across trials. Neither the main effect of Experiment, $F(1, 22) = 2.91$, $P > 0.05$, nor the Experiment × Trial interaction, $F(5, 110) = 0.35$, was significant, suggesting that the infants in Experiments 2B and 2C did not differ reliably in their responses to the habituation event.

A second analysis compared the infants' looking times at the test events. These looking times were compared by means of a $2 \times 2 \times 2 \times 3$ mixed-model ANOVA with Experiment (2B or 2C) and Order (novel/orange-cylinder or familiar/yellow-cylinder event first) as between-subjects factors and with Event (novel/orange-cylinder or familiar/yellow-cylinder event) and Test Pair (first, second, or third pair of test-trials) as within-subject factors. The only significant effect was that of Test Pair, $F(2, 100) = 3.30$, $P < 0.05$, indicating that the infants looked reliably less across test pairs. Four planned comparisons were conducted. The first two revealed that the mean looking time of the midpoint infants in Experiment 2B at the novel event ($M = 36.5$, SD = 22.3) did not differ reliably from the mean looking time of the infants in Experiment 2C at either the orange-cylinder event ($M = 39.5$, SD = 21.3), $F(1, 100) = 0.35$, or the yellow-cylinder event ($M = 37.7$, SD = 20.6), $F(1, 100) = 0.05$. The other two comparisons indicated that the mean looking time of the midpoint infants in Experiment 2B at the familiar event ($M = 26.7$, SD = 18.5) was reliably different from the mean looking time of the infants in Experiment 2C at both the orange-cylinder event, $F(1, 100) = 6.35$, $P < 0.025$, and the yellow-cylinder event, $F(1, 100) = 4.66$, $P < 0.05$.

6.3. Discussion

The infants in Experiment 2C looked reliably longer at the test events they were shown than did the male infants in Experiment 2. Furthermore, the looking times of the infants in Experiment 2C were similar to those of the infants in the midpoint condition in Experiment 2B at the novel test event, and reliably greater than the looking times of these same infants at the familiar test event. Together, these results suggest that the infants in Experiment 2C (a) expected same-size cylinders to have similar effects on the length of the bug’s trajectory; (b) used the habituation event to calibrate their predictions about the test events and so expected the bug to travel to the middle of the track with the medium orange and yellow cylinders, just as it had with the medium blue cylinder; and hence (c) were surprised in the test events when the bug rolled to the end of the track, violating their predictions.

These results provide evidence against the hypothesis that the male infants in Experiment 2 failed to show a reliable preference for the small- over the large-cylinder event because they were unable to engage in calibration-based reasoning. The infants in Experiment 2C used the information they had gained about the medium blue cylinder to predict how far the bug should roll when hit by the medium yellow and orange cylinders.

Why, then, did the male infants in Experiment 2 fail to look reliably longer at the small- than at the large-cylinder event? At least two possibilities remain. The first is that, although the infants were able to engage in calibration-based reasoning, as shown in Experiment 2C, their ability to do so was still very limited. It could be suggested, for example, that 5.5-month-old male infants can apply their calibration-based reasoning to novel objects that differ from the calibration object in color or size, but not both. Such an account would explain both why the infants in Experiment 2C could make predictions about the medium yellow and orange cylinders, and why the infants in Experiment 2 could not make predictions about the small orange and large yellow cylinders. In future experiments, it should be possible to test this hypothesis directly by presenting 5.5-month-old male infants with test events involving, for example, small and large blue cylinders.

A second explanation for the responses of the male infants in Experiment 2 is that these infants had not yet learned that, in a collision between a moving and a stationary object, the size of the moving object affects the distance traveled by the stationary object.

As was mentioned in Section 1, one important assumption of our approach is that infants are born with a learning mechanism that guides their identification of variables (e.g. Baillargeon, 1994a; Baillargeon, 1995; Baillargeon, 1998; Baillargeon et al., 1995). Another assumption is that, for infants to identify a variable, they must be exposed to data – observations or manipulations – from which the learning mechanism can abstract the variable. This line of reasoning suggests that prior to about 5.5–6.5 months of age infants are exposed to data from which they can learn the size/distance relation explored here. It is not clear at present what these data typically involve, though they might conceivably consist of infants striking or kicking objects with greater or lesser force and eventually noticing that, the stronger the impact, the greater the objects' displacement.[5]

Why should male infants lag behind female infants by a few weeks in learning about the size/distance relation examined here? Our intuition is that this difference is tied to the slower development of male infants' binocular depth perception. Research by Held et al. (e.g. Bauer et al., 1986; Gwiazda et al., 1989a,b) indicates that, compared to female infants, male infants show slower development of stereopsis during the 3rd to the 6th months of life. Given this evidence, one might propose that male infants are slightly later than female infants at detecting the size/distance relation examined here because their depth perception provides them with less accurate information about the distance traveled by objects when hit (e.g. how far a suspended toy swings when struck or kicked). It would not be at all surprising if infants with a less mature depth perception – be they males or younger females – were slower at gathering data about objects' displacements than were infants with a more mature depth perception.

Although both the limited-reasoning and the limited-knowledge explanations offered above are logically possible, we believe that the limited-knowledge explanation is more likely, because sex differences have been found in other physical knowledge experiments that did not require infants to engage in calibration-based reasoning (e.g. Baillargeon and DeVos, 1991; R. Baillargeon, H. Raschke, and A. Needham, unpublished data). Consider, in particular, the results of the support experiments summarized in Section 1 (R. Baillargeon, H. Raschke, and A. Needham, unpublished data; see Baillargeon, 1995, and Baillargeon et al., 1995; for reviews). The results indicated that female infants aged 4–4.5 months expect an object to be stable when released on but not against a surface, whereas male infants do not demonstrate the same knowledge until a few weeks later, at 5–5.5 months of

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[5] Piaget (1952) reported many observations about his infants' systematic actions on objects that seem especially relevant here. For example, after noticing the doll Piaget has hung over her feet, Lucienne, aged 0; 5(1) (or 5 months, 1 day), 'gropes until she has felt contact between her naked foot and the doll: she then increases her movements. Same reaction at 0; 5 (7) and the days following' (p. 159). Similarly, upon noticing the wooden Pierrot Piaget has hung before her, Lucienne, aged 0; 6(2) (or 6 months, 2 days), 'strikes the toy more and more vigorously, without trying to grasp it, and bursts out laughing at the Pierrot's antics' (p. 167).

age. It seems to us likely that the sex effects observed in these and in the present experiments stem from the same cause and reflect the slower maturation of male infants' depth perception. Infants who have difficulty judging whether an object is resting against a surface when released, or how far an object travels when hit, would be expected to be slower at detecting the regularities embedded in these events.[6]

If we accept the limited-knowledge explanation, then the results obtained with the 5.5-month-old male infants in the present research suggest the following three conclusions. First, the infants did not perceive the bug trajectory associated with the medium blue cylinder in the habituation event to be arbitrary and as such as likely to vary capriciously from one cylinder to the next; rather, they expected like cylinders to have like effects. Second, the infants attached little significance to the color differences between the medium blue, orange, and yellow cylinders: the infants expected all three cylinders to consistently propel the bug the same distance and they were surprised when this expectation was violated. Finally, the infants attended to the size differences between the small, medium, and large cylinders. Lacking any knowledge of the size/distance relation, however, the infants had no basis for predicting whether these three cylinders should propel the bug the same or different distances. As a result, the infants showed little surprise at the novel trajectories associated with the small and large cylinders. Exactly why the infants expected the same- but not the different-size cylinders to have the same effect on the bug's displacement – because of general beliefs about objects' interactions, or because of more specific expectations about collision events – is an interesting question for future research.

7. Conclusion

As was discussed in Section 1, the general goal of our research program is to trace the development of infants' knowledge about collision events, and to specify the innate and experiential factors that contribute to this development. Our prior

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[6] We do not believe that all sex differences observed in infants aged 4–6 months of age reflect differences in physical knowledge. In some cases, male infants may possess the same knowledge as female infants, but be unable to reveal this knowledge because their depth perception is too limited to adequately perceive the spatial arrangement of the objects used in the test events. As an example, consider the car and mouse experiment described in Section 1 (Baillargeon and DeVos, 1991). Unlike 4-month-old female infants, 4-month-old male infants (and 3.5-month-old female infants) tended to look equally at the on-track and off-track events, most likely because they could not determine in the few seconds that the screen was raised whether the box was located in or out of the car's path.

We have argued that the slow maturation of male infants' depth perception causes them to fail at a number of tasks, either because it hinders their acquisition of the relevant physical knowledge, or because it makes it difficult for them to process the layout of the test situations. This line of reasoning gives rise to the following question: why should male infants have such a protracted development relative to female infants? There is evidence in both the child and adult literature that male subjects outperform females in various spatial reasoning tasks (e.g. Linn and Petersen, 1985; Vasta et al., 1993; Voyer et al., 1995); one interesting possibility is that the slow maturation of male infants' depth perception helps make possible this spatial advantage, perhaps through the assimilation of more brain area, or through the establishment of more neural interconnections.

research (Kotovsky, 1992; Kotovsky and Baillargeon, 1994) indicated that (a) by 5.5 months of age, infants expect a stationary object to be displaced when hit by a moving object and (b) by 11 months of age, infants realize that how far the stationary object is displaced depends on the size of the moving object. The present research added to these earlier findings by showing that, by about 5.5–6.5 months of age, infants have already learned this size/distance relation.

Our continuing work has focused on several directions. One has been to explore whether infants younger than 5.5 months of age possess any expectation about collision events (Kotovsky and Baillargeon, 1998a). A second research direction has been to examine what additional variables infants older than 6.5 months consider in reasoning about collision events (Kotovsky and Baillargeon, 1998b; L. Kaufman, R. Baillargeon, and L. Kotovsky, unpublished data). The results of these investigations, together with the present results, point to the following sequence in the development of infants' expectations about collision events. By 2.5 months of age, infants have formed an initial concept of collision centered on an impact/no-impact distinction: they expect a stationary object to be displaced when hit by a moving object, and to remain stationary otherwise. By 5.5–6.5 months, infants have added a variable to their initial concept: they appreciate that stationary objects are typically displaced farther when hit by larger as opposed to smaller moving objects. Finally, at about 8 months of age, infants have begun to differentiate among stationary objects between those that are likely to be displaced when hit and those that are not: at this stage, infants expect objects with a salient vertical dimension to remain stationary when hit, and objects without such a dimension to be displaced when hit (we suspect that this variable is identified when infants begin to crawl and pull themselves up on the legs of tables and chairs, the slats of cribs, and so on). Current experiments focus on the responses of 9-month-old infants to collision events, and more particularly on whether these older infants take into account not only the verticality but also the width of stationary objects in judging whether they should be displaced when hit.

In addition to examining what variables infants identify in the course of learning about collision events, we are also exploring what strategies infants are able to use to reason about these variables. Computational models of everyday physical reasoning (e.g. Forbus, 1984) commonly distinguish between two types of reasoning strategy: quantitative and qualitative strategies. A strategy is said to be *quantitative* if it requires subjects to encode and use information about absolute quantities (e.g. object A is 'this' large, where 'this' stands for some absolute measure of A's size). In contrast, a strategy is said to be *qualitative* if it requires subjects to encode and use information about only relative quantities (e.g. object A is larger than object B). Our prior research on infants' physical reasoning suggests that, after identifying a continuous variable as being relevant to an event category, infants are typically able to reason about the variable first qualitatively and only after some time quantitatively (e.g. Baillargeon, 1991; for reviews, see Baillargeon, 1994a; Baillargeon, 1995).

To illustrate, consider the results of experiments on infants' reasoning about unveiling events (for reviews, see Baillargeon, 1994a; Baillargeon, 1995). In one experiment, 13.5- and 12.5-month-old infants were shown two test events. At the start of each event, the infants saw a cloth cover with a small protuberance. Next, the cover was hidden by a screen, and a hand reached behind the screen's right edge twice in succession, reappearing first with the cover and then with a small (small-dog event) or a large (large-dog event) toy dog. The 13.5-month-old infants looked reliably longer at the large- than at the small-dog event, suggesting that they (a) realized that the size of the protuberance in the cover could be used to reason about the size of the object under the cover; (b) remembered the size of the protuberance after the cover was hidden from view; and (c) judged that the small but not the large dog could have been hidden under the cover. These and control results suggested that, by 13.5 months of age, infants are able to reason quantitatively about the size of the protuberance in a cover: they can remember the absolute size of the protuberance and compare it to the size of the object retrieved from under the cover.

In contrast to the 13.5-month-old infants, the 12.5-month-old infants tended to look equally at the small- and large-dog events. However, positive results were obtained with these younger infants when a second, identical cover was added to the right of the screen; each dog, after it was retrieved, was held next to the second cover, allowing the infants to compare in a single glance the size of the dog to that of the cover. This visual comparison was essential for the infants' success: when the second cover was placed to the left rather than to the right of the screen, preventing any direct comparison of the dog and second cover, the infants no longer showed surprise at the large dog's retrieval. These and control results suggested that, at 12.5 months of age, infants can reason about the size of a protuberance in a cover only qualitatively: they can judge whether an object could have been hidden under a cover only if they are able to visually compare the size of the object to that of an identical cover.

In the present research, the infants did not have to encode and remember the absolute size of the habituation cylinder in order to compare it to the size of each test cylinder: at the start of each test trial, the small, medium, and large cylinders lay side by side on the apparatus floor. In a recent experiment (L. Kotovsky and R. Baillargeon, unpublished data), we asked whether 7.5- and 6.5-month-old infants tested in the midpoint condition would still show a reliable preference for the small- over the large-cylinder test event if only one cylinder was present in the apparatus in each test trial. Under these conditions, the infants had to remember the absolute size of the habituation cylinder in order to (a) compare it to the size of the cylinder used in each test trial and (b) judge whether this cylinder should propel the bug the same or a different distance than the habituation cylinder. The 7.5-month-old infants looked reliably longer at the small- than at the large-cylinder event, whereas the 6.5-month-old infants tended to look equally at the two events. These results mirror those described above for the 13.5- and 12.5-month-old infants' responses to the small- and large-dog unveiling events (Baillargeon, 1994a; Baillargeon, 1995). More generally, the results of these collision experiments, together with the present results, provide further support for the conclusion that, after infants identify a continuous variable as being relevant to an event category, they are able to reason first qualitatively and only after some time quantitatively about the variable.[7]

All of the preceding research is helping us to achieve a clearer picture of the development of infants' knowledge and reasoning about collisions between inanimate *inert* objects (for further discussion, see Kotovsky and Baillargeon, 1994). Additional research by Leslie, Oakes, Cohen and their colleagues (e.g. Leslie, 1982; Leslie, 1984b; Leslie, 1994; Leslie, 1995; Leslie and Keeble, 1987; Cohen and Oakes, 1993; Oakes, 1994; Oakes and Cohen, 1995) is helping us understand how infants reason about collisions between inanimate *self-moving* objects. In what follows, we briefly summarize some of the findings obtained by Leslie (Leslie, 1982; Leslie, 1984b; Leslie and Keeble, 1987) and Oakes (1994) with infants aged 6–7 months and then discuss the implications of these findings for the present research.

7.1. Research with self-moving objects

Infants in experiments with inanimate self-moving objects (e.g. Leslie, 1982; Leslie, 1984b; Leslie, 1994; Leslie, 1995; Leslie and Keeble, 1987; Cohen and Oakes, 1993; Oakes, 1994; Oakes and Cohen, 1995) are typically presented with filmed or videotaped events depicting the successive motions of two similar objects; the objects' motions are either temporally and spatially contiguous or separated by a temporal or a spatial gap. For example, Leslie and Keeble (1987) habituated 6-month-old infants to one of two filmed events: (a) a contiguous event in which a red brick approached and contacted a green brick, which immediately moved off; or (b) a non-contiguous event in which the two bricks' motions were separated by a 0.5-s delay. Following habituation, the infants watched the same event in reverse. The infants looked reliably longer when the contiguous than when the non-contiguous event was reversed, suggesting that they perceived the two events differently. Oakes (1994) obtained similar results with a different procedure. She habituated 7-month-old infants to one of three computer-generated events: (a) a contiguous event in which a blue ball approached and contacted a red ball, which immediately moved off, (b) a non-contiguous event in which a 0.75-s delay separated the motions of the

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[7] In this discussion, we focused exclusively on the size of the cylinder. One could ask why the distance traveled by the bug did not show the same qualitative-quantitative pattern observed for the cylinder's size. After all, the 6.5-month-olds in Experiment 1, the 5.5-month-old females in Experiment 2, and the 5.5-month-old males in Experiments 2B and 2C could not have succeeded at the tasks they were given without remembering how far the bug rolled during the habituation event. Does this suggest that the infants were able to remember the absolute distance traveled by the bug during the habituation event, but not the absolute size of the habituation cylinder? We think not. We believe that the infants in the present research had no difficulty remembering the distance traveled by the bug because they encoded this information in qualitative rather than in quantitative terms. That is, the infants in the midpoint condition encoded not 'the bug travelled about 30 cm', but rather 'the bug stopped at about the middle of the track', or 'in front of me', or 'in front of this portion of the back wall'. Similarly, the infants in the endpoint condition encoded not 'the bug travelled about 81 cm', but rather 'the bug stopped against the right wall of the apparatus'. These qualitative encodings were easy for the infants to remember and retrieve. It is only the representation of absolute quantitative information that poses problems for infants initially, until they have had sufficient experience – typically within a month or so – to demonstrate a marked improvement in their performance.

first and second ball, and (c) another non-contiguous event in which a 12-cm gap separated the two balls' motions. The infants habituated to the contiguous event dishabituated to both of the non-contiguous events, but the infants habituated to either of the non-contiguous events tended to dishabituate only to the contiguous event. These results again suggested that the infants viewed the contiguous and non-contiguous events differently.

On what basis did the infants in the preceding experiments distinguish between the contiguous and non-contiguous events they were shown? Both Leslie (Leslie and Keeble, 1987; Leslie, 1994; Leslie, 1995) and Oakes (Oakes, 1994; Oakes and Cohen, 1995) have argued that the infants interpreted the differences between the events in causal terms. That is, when faced with a contiguous event, the infants assumed that the first object brought about or caused the second object's motion; when shown a non-contiguous event, however, the infants concluded that the two objects' motions were independent. Leslie has further speculated that what lay at the core of the infants' causal judgments was a primitive notion of force (Leslie, 1994; Leslie, 1995). According to this proposal, the infants' representations of each contiguous event included a simple unidirectional force – a push – that was exerted by the first object onto the second and brought about its displacement.

7.2. Infants' reasoning about inert and self-moving objects

Comparison of our findings (e.g. Kotovsky, 1992; Kotovsky and Baillargeon, 1998a,b) with those of Leslie and Keeble (1987) and Oakes (1994) suggests that, by 6–7 months of age, infants have different expectations about inanimate inert and self-moving objects. In the case of inert objects, infants are surprised if a stationary object (a) is not displaced when hit or (b) is displaced when not hit. In the case of self-moving objects, however, neither of these statements appears to be true. One striking aspect of the habituation data collected by Oakes and Leslie and Keeble is that the infants tended to look equally whether they were shown the contiguous or non-contiguous events. These data suggest that infants aged 6–7 months are not surprised to see a self-moving object (a) remain stationary when hit or (b) move off when not hit.[8] It should perhaps be

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[8] It might be objected that the differential responses described here could stem from infants' differential expectations not for inanimate inert and self-moving objects, but rather for inanimate and animate objects. There has been a great deal of speculation and research concerning infants' ability to distinguish between animate and inanimate objects (e.g. Gelman and Spelke, 1981; Golinkoff et al., 1984; Legerstee et al., 1985; Premack, 1990; Johnson and Morton, 1991; Mandler, 1992; Bertenthal, 1993; Woodward et al., 1993; Meltzoff and Moore, 1994; Gergely et al., 1995; Poulin-Dubois et al., 1996). Our own intuition, however, is that, beyond this fundamental distinction, infants also draw a secondary distinction, among inanimate objects, between those that can move on their own and those that cannot. According to this view, infants would classify a brick, a ball, or a box as self-moving if they saw it initiate or alter its own motion; however, further evidence would be needed for infants to view the object as an animate rather than merely an inanimate self-moving object. Such evidence might take the form, for example, of non-rigid motion, contingent responding, or the pursuit or avoidance of goals. We have recently undertaken experiments involving otherwise identical inert and self-moving objects, to test our intuitions and more generally shed light on the development of infants' expectations about these different objects.

stressed that all of the responses produced by the infants in these experiments are similar to those adults might produce. To illustrate, we would be surprised to see a golf ball (a) remain on its tee after being hit squarely by a club or (b) fly through the air even though a club missed it by a foot. We would not be surprised, however, to see one car stop and another car move off, whether or not the two cars' motions were separated by a temporal or a spatial gap.

The differences in infants' responses to collisions involving inert and self-moving objects raise several fascinating questions for future research (see Kotovsky and Baillargeon, 1998b for further discussion). In particular, how do infants come to distinguish between these two types of inanimate object? How do they characterize or account for the differences between them? And how do infants identify the various event contexts in which inert and self-moving objects may be expected to behave differently?

In the present discussion, however, we focus on the similarities rather than the differences in infants' reasoning about inert and self-moving objects. We find very compelling Leslie's (Leslie, 1994; Leslie, 1995) proposal that infants possess a primitive notion of force that informs their representations of all collision events, whether they involve inert or self-moving objects. Infants' notion of force might constitute a part of their innate representational vocabulary – the vocabulary of elements and relations that infants draw on when forming their representations of physical events. Previous research suggests that this vocabulary includes simple physical categories such as 'object' and 'surface', with object being defined initially as any collection of adjacent, bounded surfaces (e.g. a cup, a shoe, a dog), and surface as any broad, two-dimensional expanse (e.g. a wall, a floor, a table's surface (e.g. Spelke, 1982; Kestenbaum et al., 1987; Termine et al., 1987; Craton and Yonas, 1990; Spelke et al., 1993; Needham et al., 1997). There is also evidence that young infants' representational vocabulary includes simple spatiotemporal relations, such as whether an object is in front of or behind another object, is adjacent to or spatially distant from another object or surface, moves immediately upon being contacted by another object or only after some delay, and so on (e.g. Yonas et al., 1979; Leslie, 1982; Yonas and Granrud, 1984; Slater and Morison, 1985; Leslie and Keeble, 1987; Slater et al., 1990; Oakes, 1994; Oakes and Cohen, 1995). Leslie's proposal adds to these prior accounts by suggesting that infants' representational vocabulary also includes mechanical information: infants would represent from birth simple force relations between objects (Leslie, 1994; Leslie, 1995).

When applied to the present research, Leslie's proposal suggests that the infants included in their representation of each collision between the cylinder and bug a unidirectional force or push exerted by the cylinder onto the bug (Leslie, 1994; Leslie, 1995). Furthermore, the fact that the 6.5-month-old infants and 5.5-month-old female infants expected the large cylinder to displace the bug farther than the medium or small cylinder, could be taken to mean that the infants expected the large cylinder to exert a greater force onto the bug, thereby producing a greater displacement. Finally, the finding that the 5.5-month-old male infants had no expectation that the bug should roll farther with the large than with the medium or small cylinder suggests that the infants had not yet learned that (a) larger objects typically exert greater forces than do smaller objects or (b) greater forces typically translate themselves into greater displacements.

Implicit in the above comments is an important assumption concerning the status of infants' notion of force. Specifically, this notion is not equated to an elaborate, full-fledged model of how forces operate in the world, an innate model that dominates infants' interpretation of mechanical events and enables them from birth to detect any or all force violations (cf. Spelke, 1994 for a discussion of innate knowledge principles). The results obtained with the 5.5-month-old males in Experiment 2 (and the results of Kaufman et al., unpublished data that were discussed earlier) suggest that infants often fail to detect even salient force violations. Such failures in turn suggest that infants' understanding of forces is initially limited and develops gradually with experience. Because of their innate representational arsenal, infants are able from the start to include forces, like mechanical arrows, in their event representations; how forces work, however, must be pieced together. Infants must learn about forces and their effects in the same way that they learn about other facets of the physical world.[9]

In Section 1, we argued that infants are born with a specialized learning mechanism that is responsible for several processes, including the formation of object and event categories and the identification of initial concepts and variables (Baillargeon, 1994a; Baillargeon, 1995; Baillargeon, 1998; Baillargeon et al., 1995). Considerable empirical research needs to be carried out before we can ascertain whether infants include force information in their representations of objects and events. From the perspective of our model, there are at least two reasons why such research is important. First, at a concrete level, the results of these investigations will literally determine how we describe infants' knowledge about specific object and event categories. For example, in the case of the present research, are infants initially learning that the larger the moving object, the farther the stationary object is displaced – or are they learning that the larger the moving object, the greater the force it exerts on the stationary object, leading to a longer displacement? What infants learn will depend on what they represent, and what they represent will in turn depend on both their innate vocabulary and their accumulated physical knowledge.

The second reason why considerations of infants' mechanical intuitions can enrich our approach is that they make room within our model for an explicit notion of mechanical causality that was hitherto lacking. Causal reasoning can be defined at a very general level in terms of an ability to detect and reason about regularities in objects' displacements and interactions with other objects. Causal reasoning can also be defined more narrowly in terms of an ability to identify mechanical sequences in which one event brings about another event through the transmission of a physical force. In our work to date, infants' reasoning about events has been characterized exclusively in terms of the first, more general type of causal reasoning. By admitting that forces may be a part of infants' event representations, however, we can make explicit the place of mechanical causality within our approach. In this new perspective, infants still bring order to their physical world by forming event categories and identifying for each category an initial concept and variables. The main

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[9] We are grateful to Alan Leslie for generously sharing his insights into these issues.

difference is that event categories are now acknowledged to fall into two broad types: those that are defined purely in spatiotemporal terms (e.g. occlusion events in which an object passes behind a nearer object), and those that depend on both mechanical and spatiotemporal relations (e.g. collision events in which a moving object approaches and impacts a stationary object).

7.3. Concluding remarks

The present research has helped us better understand the development of infants' knowledge about collisions between inert objects and the complex factors that affect this development. Comparing infants' responses to collisions involving inert and self-moving objects not only has brought to light interesting differences, but more generally has given us a deeper appreciation for the remarkable sensitivity with which infants reason about objects and events. Finally, applying Leslie's proposal about infants' innate notion of force to the present findings has both enriched their interpretation and made more explicit the role of representational constraints in our model of infants' acquisition of physical knowledge (Leslie, 1994; Leslie, 1995).

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